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THE USE OF HIGH-FREQUENCY INFRARED RADIOMETRY FOR REMOTE ATMOSPHERIC PROBING WITH HIGH VERTICAL RESOLUTION

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1. INTRODUCTION

The first experiment designed to obtain a three dimensional temperature sounding of the stratosphere and troposphere from a satellite is expected to be launched within a day or two of our meeting. The time, therefore, is particularly appropriate to look ahead to future satellite infrared measurements that will furnish the increasing requirements of a developing numerical weather prediction routine. In this paper I will discuss the two particularly important problems that we will eventually have to face: the necessity of obtaining soundings of temperature and water vapor content of the lower troposphere with sufficient vertical resolution to determine the exchange of heat and moisture between the surface and the atmosphere; and the necessity of obtaining these soundings even under the usual conditions of at least partial cloud cover. The means discussed for solving the first problem will be the use of emission measurements in the high frequency end of the thermal infrared, in particular in the 4.3μ band of CO_2 and the 6.3μ band of H_2O. The means discussed for solving the second problem will be supplementary scanning with high area resolution.

2. THE PROBLEM OF VERTICAL RESOLUTION

The relevance of measurements at high frequency lies in the fact that the information-carrying quantity is not the transmission differential [e.g. $(d\tau_\nu/d\ell np)\,d\ell np$] in which form weighting functions are usually presented but rather the increments of energy loss to space [i.e. $B_\nu\,(d\tau_\nu/d\ell np)\,d\ell np$], or, more precisely, the differences of this latter quantity.

At microwave frequencies, where the black-body function B_ν is a linear function of temperature, its effect on the weighting function is small. In contrast, the effect is appreciably and increasingly greater at higher frequencies, where B_ν becomes proportional to $\exp(-h\nu/kT)$. In the 4.3μ CO_2 band the relative variation of B_ν with temperature is 3.5 times as great as in the 15μ CO_2 band.

Thus, for measurements of thermal radiation in regions of the atmospheric emission spectra sufficiently far removed from each other, such as the 4.3μ CO_2 band, the 15μ CO_2 band and the 5 mm O_2 band, the relative contribution of the different layers of the atmosphere will be markedly different from one band to another, even if the frequencies chosen are such as to have equal optical depths for the different bands.

In regions of the atmosphere where the temperature normally varies monotonically with height, the effect of the black-body function B_ν is to sharpen the weighting function in the direction opposite to the temperature gradient (i.e. on the low temperature side). Weighting functions, with and without the factor B_ν are presented in Figure (1), which illustrates that this effect is particularly marked in the 4.3μ CO_2 band. The calculations were made by Dr. Robert A. McClatchey of AFCRL, assuming that the temperature distribution is given by the U.S. Standard Atmosphere.

It is seen that the effect of the B_ν factor is to make the upper part of the tropospheric weighting functions much more horizontal. Since the temperature information is contained in the difference between consecutive weighting functions, it is evident that the effect of the B_ν factor at these high frequencies is to restrict the information to very narrow strata of the atmosphere. I expect that satellite measurements at carefully chosen frequencies in the 4.3μ band of CO_2 will allow a determination of the temperature structure of the lower troposphere with at least 100 mb resolution. Much higher vertical resolution will be obtained in the upper stratosphere. Such resolution would be impossible in practice from measurements in the 15μ CO_2 band or 5 mm O_2 band, no matter how accurately they are made, because the wider weighting functions would not allow the determination of a unique sounding in comparable detail.

To obtain this vertical resolution from measurements in the 4.3μ CO_2 band, spectral band passes of about 20 cm^{-1} width are required. Detectors having signal-to-noise values greater than 100 over such a band pass for incident radiation from sources with temperature 210° K or greater are readily available; and, in fact, a spectrometer having these characteristics has been built and flown in a balloon (Shaw et al., 1967).

Figure 2, which was also computed and prepared by Dr. McClatchey shows the weighting functions, with and without the black-body factor, for selected frequencies in the 5.3μ water vapor band. Again the U.S. Standard Atmosphere was assumed to represent the temperature distribution; the total water content was assumed to be 2 gm cm^{-2}; and its concentration in the troposphere was assumed to fall off with the third power of the pressure.

Again the effect of the factor B_ν is seen to sharpen the upper part of the weighting function, although it is not so marked as in the higher frequency region near 4.3μ. However, because the decrease of mixing ratio with height has the same effect, the final weighting functions are quite similar to those of Figure 1. Thus the water vapor distribution in the lower troposphere can also be expected to be obtained with a resolution of 100 mb or better, by measurements in the 6.3μ band in conjunction with measurements in the 4.3μ CO_2 band.

The disadvantage of the high frequency bands in obtaining soundings is the insensitivity of the outgoing radiation to changes in temperature or humidity at the coldest levels of the atmosphere. To remedy this shortcoming, it will probably be necessary to supplement the high frequency measurements with a few measurements at lower frequencies, e.g., in the rotational water band and the 15μ CO_2 band, or, better yet, with use of microwave measurements in the region of O_2 and H_2O lines. To obtain the best specification of the temperature and moisture field, an ideal sensing system would sample outgoing radiation at selected wave-lengths from 3μ to 3 cm.

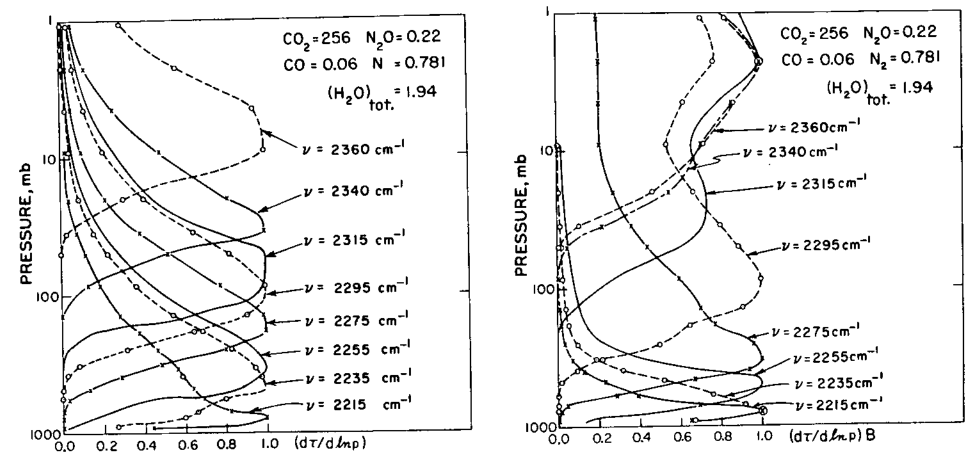

FIG. 1. Weighting functions for 4.3μ band of CO_2, without and with black-body factor (by R. A. McClatchey).

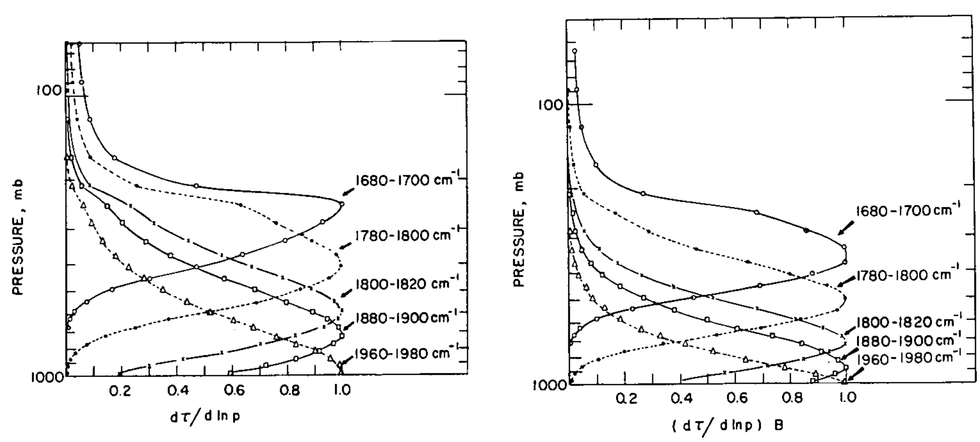

FIG. 2. Weighting functions for 6.3μ band of H_2O, without and with black-body factor (by R. A. McClatchey).

3. THE PROBLEM OF PARTIAL CLOUD COVER

The parts of the atmosphere below overcast cloud tops are inaccessible to infrared sounding from above, and a sounding of the entire atmosphere would require the use of microwave frequencies. However, for the reasons given above, it is essential that selected spectra of the higher frequency infrared flux be obtained wherever possible, including conditions of partial cloudiness, which are characteristic of most of the earth's area.

The resolution of the cloudiness problem probably requires area scanning of the field of view with considerably greater angular resolution than would be required for cloudless conditions. This is the procedure in a specific experiment suggested by W. L. Smith (1967, 1968). The increased angular resolution would be accomplished at the sacrifice of spectral resolution and therefore of the vertical resolution of the derived sounding. While this trade-off may be desirable in the immediate future to provide a useable coverage of the area of the earth, the highest possible vertical resolution will eventually be essential. I suggest that this can be accomplished in the presence of broken clouds by the supplementary use of broad-band, narrow-angle measurements. I understand from Dr. Sigmund Fritz that he is intending, along these lines, to use the HRIR measurements from NIMBUS B to help interpret those from the SIRS experiment in the presence of clouds.

In order to obtain maximum coherence of the broad-band with the narrow-band measurements, it is planned to include among the future modifications of the spectrometer system of Shaw et al. (1967) an array of broad band filters, centered at around 5μ, in the plane of the grating. They will have considerably smaller field-of-view and integration time than the narrow-band detectors, and will be oriented in such a fashion as to use the satellite motion to break the narrow-band field-of-view into say a five-by-five array of smaller areas. It is almost obvious that the combined system of narrow-band and wide-band measurements can be interpreted in terms of fractional cloud amount and temperature and height of the cloud tops, as well as the air temperature distribution, under conditions of one or two stratified layers of broken clouds. More complicated cloud distributions will probably require powerful inversion techniques, such as the one discussed in the next section and described in the appendix.

Two points should be mentioned concerning the effects of the cloudiness on the temperature inversion when use is made of the 4.3μ CO_2 band. The first is that the scattered sunlight during the daytime will interfere with the temperature inversion. In the absence of clouds, the bulk of the scattered and reflected light will come from the ground, and its effect on the spectrum of the total outgoing radiation will depend on the surface reflectivity, which can be determined by detectors located at atmospheric windows on both sides of the 4.3μ band. This will only affect the lower part of the sounding, as the atmosphere is completely opaque in the central part of the band. In the presence of daytime clouds, particularly high clouds, the entire spectrum will be affected, and it will be necessary to determine their amount, by the above-mentioned or other technique in order to determine the temperature inversion.

The second point is that the outgoing thermal radiation in the 4.3μ band is quite insensitive to small changes in cloudiness. This is because of the strong variation of the black-body radiation with temperature. As an example, if the inversion were performed neglecting the presence of a twenty per cent cloud cover at moderate altitude, the temperatures obtained would be off by less than 5° C.

Thus the strong temperature dependence of the black-body radiation at 4.3μ not only increases the temperature sensitivity of the measurements; it also makes the 4.3μ CO_2 band particularly appropriate for obtaining soundings in the presence of broken clouds.

4. THE DETERMINATION OF THE PROFILE

The problem of obtaining the profile of temperature, moisture and clouds from the spectrum of outgoing radiation is very difficult. All of the published methods of solving this problem have following the original suggestion (Kaplan, 1959, 1961) of performing a matrix inversion and have tried to save computation time by linearization of the transfer equation. This has proved to be impossible without introducing damping functions, which would by their nature not allow the high vertical resolution that will eventually be necessary.

I wish to report at this time a beautiful and powerful new approach to this problem. Dr. M. T. Chahine has utilized an important physical property of the outgoing radiation to develop a relaxation method that should be much less sensitive to errors in measurement. It is highly convergent and does not require the time-consuming matrix inversion. I am attaching, as an Appendix to this report, a paper by Dr. Chahine describing his method for the special case of a temperature sounding under cloudless conditions determined from the spectrum of the 4.3μ CO_2 band. Note in particular the high vertical resolution obtained near the surface.

Chahine's method will be extended in an attempt to incorporate measurements in the 15μ CO_2 band, the 5 mm band of O_2, the 6.3μ and rotational bands of H_2O, and the effects of clouds. It should eventually be capable of incorporating all of this into real-time computations of the detailed state of the atmosphere.

The promise of obtaining sufficiently detailed soundings of the atmosphere for immediate use in numerical weather prediction routines appears to be very bright.

5. SOUNDING FROM THE GROUND

Because of the pressure broadening of spectral lines, sounding from above allows the instrument to receive measurable amounts of radiation from all layers of the atmosphere. This characteristic of pressure-dependence of line shapes is a disadvantage for sounding from below. However, the technique may be of some use, under special circumstances, for sounding the air in the immediate vicinity of the ground* by measurements from a spectrometer or radiometer located at the surface. The strong temperature dependence of the black-body function at high frequencies again makes the 4.3μ CO_2 band and the 6.3μ H_2O band particularly appropriate for this purpose.

In order to assess the feasibility of sounding from the ground, I have calculated the downward radiation at five frequencies in the 4.3μ CO_2 band as functions of the temperature distribution. The atmosphere has been divided into layers given by the first column of Table 1. For ease in computation, each layer was assumed to be isothermal and the spectrum was assumed to be composed of strong, randomly-spaced lines, so that the transmission could be represented by an approximation to Equation (9) of Kaplan (1953) in the form $\tau = \exp(-a_\nu \sqrt{z})$, where z is the height above the ground. The constants a_ν were obtained from the laboratory data of Howard, Burch and Williams (1956), matched to a pressure of one atmosphere.

The downcoming radiation is plotted in Figure 3 for 20 cm^{-1} intervals centered at 2230, 2250, 2270, 2290 and 2310 cm^{-1}, and the points connected with straight lines. The bottom curve represents the "sounding" given by the second column of Table 1; the other curves are for the same sounding, except for a 5°C increase in the layer indicated.

It is seen from Figure 3 that the spectrum is quite sensitive, both quantitatively and qualitatively, to the temperature distribution in the first few hundreds of meters in the atmosphere. Thus measurements from below should provide data useful for determination of heat and moisture exchange between the atmosphere and the surface.

The results, in terms of percentage variation in downcoming radiation for a 1°C change of temperature in the specified layers, are also given in the last five columns of Table 1. It is seen that the sensitivity greatly decreases above the first kilometer. The approximations used to obtain the transmission function are such as to make the sensitivity to changes in the upper levels appear even greater than it is. Thus the sounding can be accomplished more easily and accurately by simpler means, such as direct sounding from tethered balloons or tall towers. The spectroscopic method may be the best from unmanned ocean buoys, however. It should be noted that, in contrast to sounding from satellites, microwave sounding from below may be competitive to the use of high-frequency bands. This is because of the possibility of obtaining higher measurement precision and because of the possibility of making almost monochromatic measurements in the wings of spectral lines, in which case the transmission function more nearly approximates the form $\tau = \exp(-a_\nu z)$.

*Dr. Atlas has pointed out that surface observations of emission in transparent regions of the spectrum can be used to determine the temperatures of cloud bases and the sides of cumulonimbus clouds. This can be done with an accuracy of about 1°C.

TABLE 1. Percentage variation of downcoming radiation in selected spectral intervals for 1°C change in various atmospheric layers.

Layer (m)	T(°K)	Center of 20 cm^{-1} interval (cm^{-1}) 2230	2250	2270	2290	2310
0-50	290	0.7	1.0	1.7	3.1	4.2
50-100	290	0.7	0.8	1.1	0.8	0.0
100-225	285	0.6	0.6	0.6	0.2	
225-400	285	0.5	0.5	0.4	0.0	
400-900	280	0.8	0.7	0.3		
900-1600	270	0.5	0.4	0.1		
1600-2500	260	0.4	0.2	0.0		
2500-3600	250	0.2	0.1			
3600-4900	240	0.1	0.0			

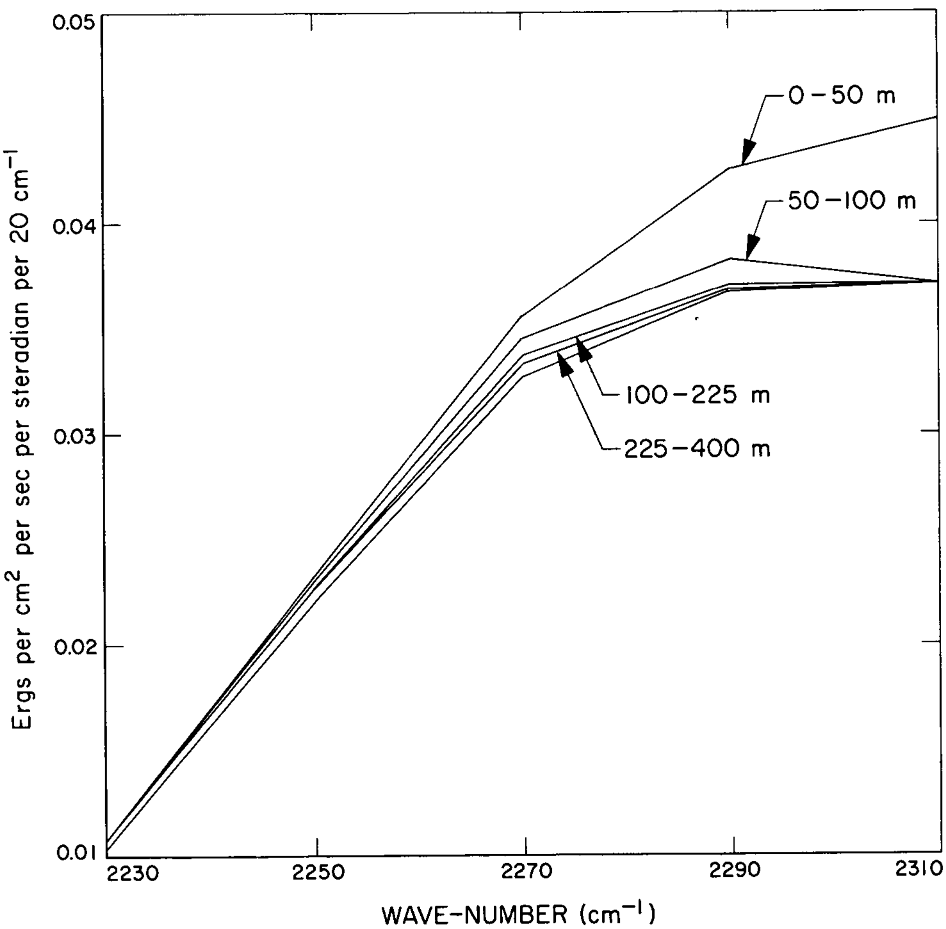

FIG. 3. Computed downward radiation for "sounding" of Table 1 (lower curve), and for same temperature distribution except for 5°C increase in indicated layer (upper curves).

ACKNOWLEDGEMENTS

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